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Single beam optical vortex tweezers with tunable orbital angular momentum

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We propose a single beam method for generating optical vortices with tunable optical angular momentum without altering the intensity distribution. With the initial polarization state varying from linear to circular, we gradually control the torque transferred to the trapped non-absorbing and non-birefringent silica beads. The continuous transition from the maximum rotation speed to zero without changing the trapping potential gives a way to study the complex tribological interactions. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4882418>]

The optical trapping of microscopic transparent objects has been demonstrated almost three decades ago.¹ Since it was shown that the gradient force can be used in three-dimensional manipulations, the technique has become attractive for numerous of fields in physical and biomedical sciences.^{2–6} The light carries linear and angular momentum that can be transferred to the illuminated objects. Angular momentum of the beam is comprised of spin angular momentum (SAM)⁷ and orbital angular momentum (OAM).⁸ SAM is associated with the polarization of the light and is always intrinsic.⁹ It can be used to rotate absorbing or birefringent particles around their axis.^{10–13} OAM comes from the azimuthal phase variation of the beam. It was demonstrated that the beam with helical phase $\varphi = l\phi$, where φ is phase, ϕ is polar angle, and l is positive or negative integer number, possess well-defined OAM with $l\hbar$.⁸ Such beams frequently referred to as optical vortices enable the rotation of transparent non-birefringent particles¹⁴ and the rotation can be both extrinsic or intrinsic.⁹ The ability to tune the angular momentum adds an extra degree of control to optical systems and has applications ranging from atomic manipulation^{15,16} to quantum information processing.^{17,18}

The transfer of total angular momentum to the trapped particles can be accomplished in several ways. Some methods involve beams without orbital momentum when the intensity distribution or the linear polarization of the beam is actively rotated in order to torque objects.^{13,19,20} By changing the state of polarization, the average spin momentum of the photon is changed and therefore, the rotation speed of the particle can be controlled.^{11,12,21} Furthermore, without introducing elliptical or linear polarizations, the transferred torque might be tuned by two counter-propagating waves of orthogonal circular polarization.^{22–24}

The control of OAM is more complicated. The change of wavefront helicity affects the geometry of the beam: the higher $|l|$, the larger diameter of the beam. As a result, the angular momentum of the beam can be defined either by the shape of the beam or by the photon density, which makes the approach limited for the task that requires a constant gradient of the intensity and tunable angular momentum. OAM of the beam can be controlled using a spatial light modulator

by generating and superimposing two optical vortices with opposite handedness²⁵ or generating fractional vortices.²⁶ However, the polarization of two vortices is the same and leads to an interference fringe pattern while in the partial vortices case, the beam does not have a symmetric donut shape. Other approaches introduce azimuthal phase gradients in holographic rings.²⁷ However, this method is limited to the range of rotation speed that is quantized and possesses azimuthal intensity gradient variations.

Here, we propose an alternative method of generating optical vortices with gradually controlled OAM, which does not have previously mentioned limitations. We used a superstructured half-wave plate polarization converter, referred to as the S-waveplate.²⁸ Such a converter is usually used to generate beams with radial/azimuthal polarization distributions. It is also known that such an optical element can be exploited to generate optical vortices.^{28,29} In this Letter, we demonstrate the continuous control of an orbital angular momentum by controlling the spin angular momentum of the input light. We also show that it does not affect the shape of the beam and can be used as an optical tweezer with tunable torque.

The operation of the S-waveplate can be described by Jones calculus. The matrix for the S-waveplate is as follows:

$$M_S = \begin{pmatrix} \cos \phi & \sin \phi \\ \sin \phi & -\cos \phi \end{pmatrix}, \quad (1)$$

where ϕ is a polar angle in the polar coordinate system. If left-handed (right-handed) circularly polarized light is transmitted through the S-waveplate, right-handed (left-handed) circularly polarized right-handed (left-handed) optical vortex is generated

$$\vec{E}_{LV} = M_S \begin{pmatrix} 1 \\ -i \end{pmatrix} = e^{-i\varphi} \begin{pmatrix} 1 \\ i \end{pmatrix}. \quad (2)$$

A spatially variant phase factor in the exponential part indicates the presence of an optical vortex with the topological charge $|l| = 1$, where a sign of l depends on the handedness of the input polarization.

Each photon of circularly polarized light carries SAM of $S = s\hbar$, where $s = \pm 1$. In the case of optical vortices, the optical momentum is contributed by OAM with $L = l\hbar$. Positive l corresponds to right-handed optical vortex and negative to

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left-handed. The S-waveplate changes the incident photon spin momentum $-S$ to S and transfers orbital momentum L to the light.

The electric field of any linearly or elliptically polarized light can be expressed as the superposition of left- and right-handed circular polarizations. In the case of elliptically polarized light, at the output of the S-waveplate two optical vortices with opposite handedness circular polarization and opposite handedness of the helical phase are produced. The overall effect of the S-waveplate on the light can be expressed as

$$(\alpha|\uparrow\rangle + \beta|\downarrow\rangle)|0\rangle \xrightarrow{\text{S-waveplate}} \beta|\uparrow, R\rangle + \alpha|\downarrow, L\rangle, \quad (3)$$

where $|\uparrow\rangle$ and $|\downarrow\rangle$ are up and down spin states of light, $|R\rangle$ and $|L\rangle$ are right and left orbital state of light. Coefficients α and β describing the state of the orbital angular momentum are same as for the spin state of light entering the S-waveplate (Fig. 1(c)). The average OAM transferred to light depends on the angle of orientation of the quarter-wave plate

$$\langle L_{out}(\theta) \rangle = -\langle S_{in}(\theta) \rangle. \quad (4)$$

In the case of linearly polarized light when the spin momentum of the photons is zero, the output is radially or azimuthally polarized light with the zero orbital momentum.

Now, we need to determine the SAM relationship with the angle of the quarter-wave plate which transforms linearly polarized light to elliptically polarized light at the first part of the beam conversion. The electric field can be described as

$$\vec{E}_E = \alpha(\theta) \begin{pmatrix} 1 \\ -i \end{pmatrix} E_0 + e^{i\Delta\Phi} \beta(\theta) \begin{pmatrix} 1 \\ i \end{pmatrix} E_0, \quad (5)$$

where θ is the angle of the quarter-wave plate, $\Delta\Phi$ is the phase difference between two polarizations. The intensity is

$$I_E = A(\theta)I_0 + B(\theta)I_0. \quad (6)$$

After some algebraic operations done by multiplying Jones matrices of a linearly polarized electric field by a quarter-wave plate matrix (Q), left/right handed circular polarizer (L/R), and expressing the intensity of the final electric field, $A(\theta)$ and $B(\theta)$ are expressed by the simple trigonometric functions

$$A(\theta) = \frac{\sin(2\theta) + 1}{2}; \quad B(\theta) = \frac{1 - \sin(2\theta)}{2}. \quad (7)$$

Now, we can see the dependence of the spin value on the orientation of the quarter-wave plate. The elliptically polarized light transmitted through the S-waveplate produces the superposition of two optical vortices with the opposite topological charges. The amplitude ratio between two vortices will correspond to the ratio between opposite circular polarizations at the input with the elliptically polarized light. The average OAM of the photon transferred by the S-waveplate is

$$\langle L(\theta) \rangle = -\langle S \rangle = -\hbar(A(\theta) - B(\theta)) = -\sin(2\theta)\hbar. \quad (8)$$

As a result, the average OAM value per photon can be not just integer but any real number in the range $[-1, 1]$ and can be controlled simply by rotating the quarter-wave plate.

In this system, the optical vortex along with the OAM also possesses the SAM. As the particles are transparent and non-birefringent, the rotation is not affected by the SAM. However, if only the OAM is required, the quarter-wave plate inserted in the optical path after the S-waveplate would eliminate the SAM from the beam.

Experimentally, the control of OAM was demonstrated with the optical trapping of fused silica beads ($1\ \mu\text{m}$ size) dispersed in aqueous solution. The experiment was performed with a regeneratively amplified diode pumped Yb:KGW

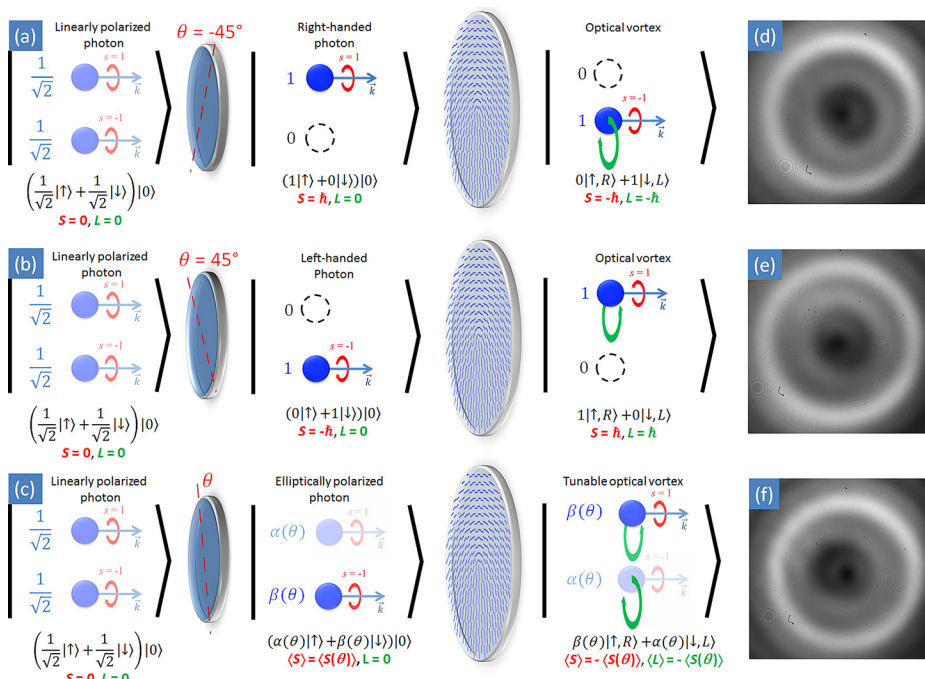


FIG. 1. The transformation of a photon transmitted through a quarter-wave plate and the S-waveplate. Linearly polarized photon passes through the quarter-wave plate (set at the angle θ) and acquires spin momentum depending on the θ value. (a) Light with spin momentum $S = \hbar$ and no OAM (right-handed circularly polarized light) transmitted through the S-waveplate changes spin momentum to $S = -\hbar$ and acquires $L = -\hbar$ (left-handed circularly polarized left-handed optical vortex). (b) Light with spin momentum $S = -\hbar$ (left-handed circularly polarized light) is transformed into the light with the spin momentum $S = \hbar$ and $L = \hbar$ (right-handed circularly polarized optical vortex). (c) Elliptically polarized light with spin momentum $\langle S(\theta) \rangle$ acquires $\langle L \rangle = -\langle S(\theta) \rangle$ and $\langle S \rangle = -\langle S(\theta) \rangle$. The measured intensity profiles of left- and right-handed optical vortices (d), (e) and a radially polarized beam (f).

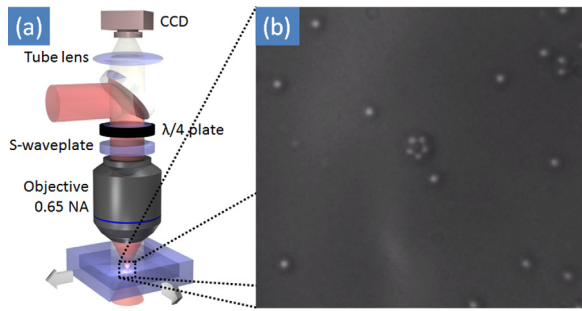


FIG. 2. (a) Experimental trapping setup. (b) The image of five fused silica beads assembled into a ring.

(Yb-doped potassium gadolinium tungstate) femtosecond laser operating at $\lambda = 1030$ nm. The average power was attenuated by a combination of a half-wave plate and Glan polarizer. To avoid the damage of silica beads the power was kept below 300 mW. Additionally, the pulse duration was stretched from 270 fs to 14 ps and the repetition rate set to the maximum (500 kHz) approaching a quasi CW state. The polarization of the laser beam was controlled by the quarter-wave plate mounted on the motorized rotational stage. After the quarter-wave plate, the laser beam passed through the S-waveplate and was focused with a $20\times$ microscope objective (0.65 NA) into the cell filled with colloidal silica beads (Fig. 2(a)). The imaging was implemented by illuminating the sample with white light and recorded using a digital camera (Fig. 2(b)).

The dependence of the torque transferred to silica beads on the OAM was characterized by rotating the quarter-wave plate with a constant angular speed of 0.5 deg/s. As the rotation speed of the quarter-wave plate was kept constant, at any given time the angle of the wave plate was known: $\theta(t) = 45^\circ - 0.5^\circ \cdot t$, where the OAM can be calculated from Eq. (8). The rotation speed of the ring was calculated by comparing the adjacent frames n and $n+1$ using the least squares method (Fig. 3). Adding the rotation angles between frames, the total rotation angle dependence on time was obtained and the dependence of the trapped beads rotation speed on the OAM and laser average power finally calculated (Fig. 4).

In the experiment, five SiO_2 beads were observed to arrange in a ring by the optical vortex produced by the S-waveplate. The lowest average power used for trapping

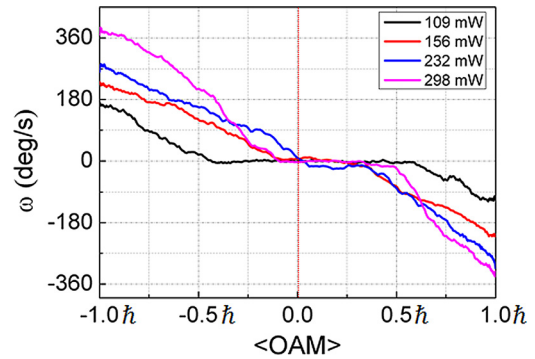


FIG. 4. Rotation speed of trapped beads dependence on the average orbital angular momentum of the photons.

silica beads was 109 mW. When the optical axis of quarter-wave plate was set to 45° the beads started rotating counter clockwise indicating the presence of the left handed optical vortex ($l = -1$) (Fig. 3(a)). As expected, the rotation direction could be changed by flipping the handedness of circular polarization (see Eq. (2)). Depending on the average power of the trapping beam the rotation speed of the beads' ring at $l = \pm 1$ varied from 90 deg/s to 360 deg/s. By changing the OAM value from $l = \pm 1$ to zero the rotation was continuously slowing down until it completely halted by the friction forces forming zero speed plateau (Fig. 4).

The overall dynamics of the rotation speed dependence on the OAM and laser average power reflects the behavior of the system in the presence of friction and inertia (Fig. 4). Additionally, the rotation is affected by imperfections of optical trap and irregularities of silica beads. Only at low OAM values all mentioned factors become significant producing strongly asymmetric zero speed plateau. The width of the plateau depends on the laser power as the higher photon density gives stronger OAM per beam at the same OAM per photon. The presence of the inertia and the system imperfections modulates the plateau introducing the dynamic and static asymmetries dependent on the direction of rotation. The observed asymmetry in rotation speed at the $l = -1$ and $l = +1$ decreases with the laser power increase when at the higher velocities the weight of the factors becomes less significant (Fig. 4).

In conclusion, we demonstrate single beam optical vortex tweezer with tunable orbital angular momentum.

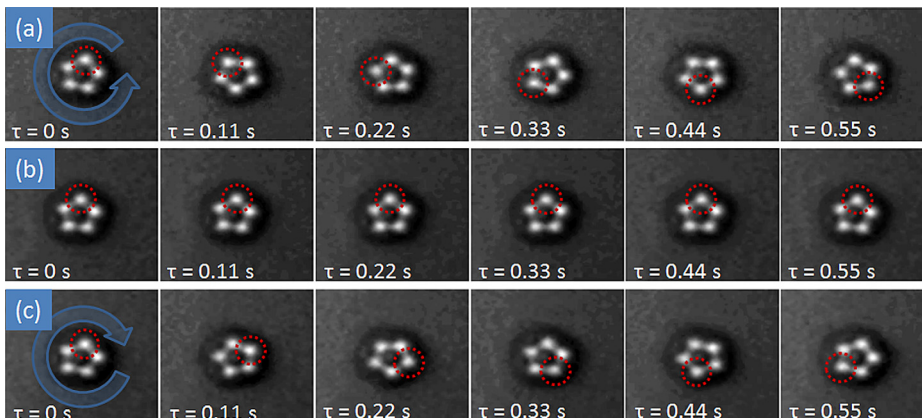


FIG. 3. The rotation of five trapped SiO_2 beads. (a) Particles rotate counter clockwise when polarization before the S-waveplate is right-handed circular. (b) Beads do not rotate when polarization before S-waveplate is linear. (c) Particles rotate clockwise when polarization before the S-waveplate is left-handed circular (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4882418.1>].

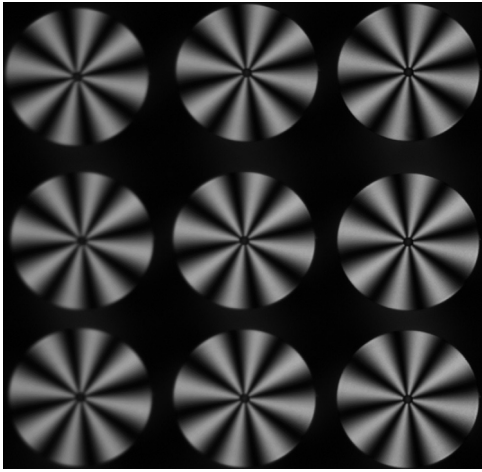


FIG. 5. The array of nine polarization converters. Cross-polarized microscope image shows that the topological charge of converters is four (eight lobes). Such converter can be used in generation of optical vortex with tunable OAM from $\langle L \rangle = -4\hbar$ to $\langle L \rangle = 4\hbar$. The diameter of the converters is $600\ \mu\text{m}$.

Changing the initial beam polarization, we continuously maximize or completely eliminate the rotation of silica beads ensuring the constant trapping potential. The observed asymmetry in rotation speed proposes a technique for measuring the interaction between trapped objects and its environment. Vortices with tunable OAM may allow precise control of particles rotation of any type materials and bio-objects such as DNA molecules measuring not only it is linear³ but also rotational response to the system. Furthermore, micro-channel based fluidic systems can be implemented applying complex micro-converter arrays with the maximum achievable rotation speed controlled by the topological charge (Fig. 5).

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